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STUDY ON OPTICAL COMMUNICATIONS FROM DEEP SPACE

INTERIM PROGRESS REPORT

7 January 1963 through 1 February 1963

AEROSPACE GROUP

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INTRODUCTION

This Interim Progress Report presents a discussion of the work performed on Contract NAS 9-879 during the period from 7 January 1963 to 1 February 1963. It concentrates on the continuance of the discussion of Laser and Optical Detector Technologies presented in the first report and with it, represents a rather comprehensive survey of existing Laser and Optical Detectors. Discussion of important characteristics of the devices relevant to optical communication is also included. An extensive bibliography is presented in the appendix.

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Project Manager
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COMMUNICATIONS STUDY

1.0 OPTICAL MASER TECHNOLOGY

In the first progress report, a preliminary survey of operating lasers and their characteristics was given. In that document, the principal concentration was on pulsed solid state and CW Gas Lasers. The following is a continuation of that survey concentrating on CW operating lasers (solid state and gas), the properties of the Gallium Arsenide lasers, and solar pumped lasers. The characteristics of operating lasers which are relevant to their use as optical communications systems components is also discussed. An extensive bibliography is included in the Appendix.

1.1 LASER CHARACTERISTICS

1.1.1 Coherence and Spectral Properties of Lasers

One of the reasons optical laser beams are thought to be suitable for applications to communications is the large degree of temporal and spatial coherence exhibited by the laser emission. Since the discovery of lasers, the properties of the laser emission has been studied extensively. In the discussion that follows we shall review some of the present knowledge of the coherence and spectral properties, and the detailed structure of the laser emission that may be of special interest in applications to optical communications.

Usually many modes oscillate simultaneously in an optical resonator. These modes have different frequencies and different spatial characteristics so that one may not be able to make use of more than one mode in a specific application. When all the modes except one are suppressed, the power that was formerly distributed over many modes is concentrated in a single mode. This mode suppression has been accomplished in a He-Ne gas laser by Kogelnik and Patel[1]. They have suppressed the unwanted longitudinal modes without decreasing the gain of the cavity so that the output power is not decreased and is concentrated in a single frequency near the center of the Doppler-broadened line. Theoretically, when the oscillator output consists of a single longitudinal mode, the light is spatially coherent across the beam cross section and the collimation of the beam is thus limited by diffraction. The beam spread of the emission of a He-Ne gas laser with four milliwatts continuous power in the 1.153 micron line has been observed to be almost diffraction limited[2]. The line shape consists of three or more components less than a few hundred cycles in width and separated by the spacing of orders in the interferometer.

The spatial coherence of a beam can be measured by observing the far field or multiple slit diffraction patterns while the time coherence is measured by the spectral line width. The mutual correlation function between any two points in the beam is given by a combination of these two effects. However, the line width of the emission of the ruby laser is not always indicative of the time coherence since the output may consist of unresolved off-axis and axial modes. These off-axis modes have been observed by Ready[3] and many others. One or more sharp components have been observed[4] with a spectral width of 6×10^{-4} Å. McMurtry and Siegman[5] have made observations on the output of a ruby laser that indicate that the line width is about 2 Mc/sec. The resonant cavity, formed by the end faces of the ruby, is able to support many resonant frequencies within the atomic line breadth. Adjacent modes are separated by about 602 Mc/sec. in the laser used in this experiment. Photo mixing of the output produced microwave signals spaced about 600 Mc/sec. apart which showed that the laser is indeed oscillating in several simultaneous axial modes separated by the proper frequency interval.

Interference patterns have been formed by the direct illumination of two slits with the light emission from the end face of a ruby. The formation of interference fringes demonstrates the phase coherence between different points on the face of the ruby[6]. Kisliuk and Walsh have made beams from the opposite ends of a ruby laser interfere and have obtained interference fringes[7]. This implies a constant phase relationship between points at different ends of the ruby, which is the expected result for a system of standing waves in a cavity. As is well known, the output of a ruby laser consists of a series of spikes of about a microsecond duration. The distribution of light across the face of the ruby, which is known to be non-uniform, need not be the same from spike to spike. If the distribution of the light does change, the interference pattern would change from spike to spike and observations made over a large number of spikes would not show interference fringes. Hence, the existence of fringes in the experiments of Kisliuk and Walsh imply, in addition to constant phase relationship, that the distribution of light across the face of the ruby must be nearly the same for all spikes.

Irregularities of the fringe patterns are also observed, which is consistent with the results of Nelson and Collins who found that the fringe patterns were displaced. Both these observations are accounted for by assuming a slight phase difference between spatially separated points on the ruby face.

The spectral purity of the emission of gas lasers is much greater than that of the ruby output. Javan et. al.[8] have found the intrinsic line width of a He-Ne gas laser to be not larger than 2 cps. The theoretical limit of the narrowness of the spectral lines is a consequence of a certain unavoidable amount of spontaneous emission. The measured line width, even though extremely small, is still several orders of magnitude greater than the theoretical limit. It should be emphasized, however, that the greater degree of monochromaticity of the gas laser does not mean that gas lasers possess a clear advantage over pulsed lasers for the purposes of communication, since present modulation techniques cannot make use of the potential band width available at optical frequencies.

The filamentary nature of the emission of ruby lasers has been frequently observed. High speed photographs[9] of the emission patterns have been made which show that the light is emitted in a pattern of small spots on the ruby face, and that the emission pattern does not change much during the pumping pulse. This is in agreement with deductions made from the observation of interference fringes discussed above. In addition, streak photographs of sufficient resolution to show the structure of a single laser spike were made. They show that within each spike is a regular oscillation of about 50 Mc/sec., and that each emitting area of the ruby produces a spike with the same 50 Mc/sec. oscillation on it, with the oscillations sometimes out of phase.

Optical masers are presently limited to either higher-power pulsed operation or relatively low-power continuous operation, and the power efficiencies of these coherent optical frequency sources, with the exception of the Ga As lasers, are still very low (less than 1 percent). Evidently what is needed is a moderately efficient, medium-power continuous source, or perhaps a high-power, efficient, pulsed source with a high-duty cycle. There is presently a considerable effort towards developing sources with these capabilities; Hughes Research Laboratory at Malibu, California and R. C. A. Laboratory at Princeton, New Jersey, to mention two, are presently concerned with the development of 10 watt continuous solid-state lasers of improved efficiency. The achievement of high-duty cycles requires flash tubes capable of repetitive high-power operation and the maintenance of low temperatures in the laser crystal. Since the power dissipated in the crystal is of the order of the power output, and efficient operation of the laser requires low temperatures, cooling the crystal is by no means a minor problem. We will not consider the problems of repetitive pulsing here, but we will discuss some features of the single pulse operation of pulsed lasers and in particular the giant pulse mode of operation.

In the usual pulsed operation of a ruby laser and other solid-state lasers, the output consists of a series of microsecond duration spikes spaced several microseconds apart. The individual spikes have a peak power of the order of a few kilowatts and the total energy in the series of spikes is about a joule. The spikes or oscillations continue so long as the input power is above the threshold for oscillation. Usually the ruby is pumped by flash lamps in pulses about a millisecond long.

In normal laser operation, oscillation occurs when the gain of the cavity exceeds the losses by a small amount. The stimulated emission causes an increased radiation density in the cavity and a subsequent depletion of the population of the excited metastable state. The population of the excited state is then decreased more rapidly than it is replenished by the pump photons. When the population of excited states is reduced below the critical number required to provide net gain in the cavity, the oscillation subsides.

This is a rough description of the production of a single laser spike. Continued pumping repopulates the metastable state and the process is repeated as long as the pumping energy is sufficiently high to obtain a net gain in the cavity. The spiking is not periodic even when the pumping energy is essentially constant. That is, there are variations in the amplitude and spacing of the laser spikes within a single pulse. There have been numerous explanations for the spiking phenomena, none of which seem to completely explain the problem. It was originally thought that the spiking was a damped oscillation and would decay when the ruby was operated continuously. This has proved not to be the case, since in the CW operation of a ruby laser the spikes have been observed to persist with essentially the same characteristics that are observed in pulsed operation. The continued spiking is characteristic of the four solid-state lasers known to have produced CW output. (CaF_2: Dy^{2+}, $CaWO_4$: Nd^{3+}, CaF_2: U^{3+} and ruby).

The output of a giant pulse ruby laser consists typically of a single high-power short-duration burst of coherent radiation. These pulses are about 10^{-8} sec. or longer and peak powers of the order of megawatts are easily obtained when proper switching techniques are used. Actually a single pulse occurs only for special switching conditions on the power regeneration to the cavity, and the output often consists of a large pulse followed by several low-power pulses. The giant pulse mode of operation is achieved by varying the power regeneration to the cavity, which is equivalent to varying the Q of the resonating cavity.

To obtain giant pulses, one pumps a ruby laser contained in an optical cavity of very high loss. This can be arranged by making the reflection losses of the cavity very large. It then requires a large population inversion in the ruby to obtain net gain and laser oscillation in the cavity. When a large population inversion is obtained and before spontaneous oscillation takes place, the reflection losses are decreased, which produces a situation where the normal threshold conditions for oscillation are greatly exceeded. When the switching of the power regeneration is sufficiently fast, a single short-duration high-power pulse is produced. The detailed structure of the pulse is governed by some fairly complicated laser dynamics and line broadening effects that are not fully understood. However, many of the gross features of the pulse structure are understood. It is known that the pulse shape is sensitive to the cavity Q switching time and that for sufficiently slow switching several low-power pulses follow the initial intense pulse. McClung and Hellwarth[10] have investigated the effect of the switching rate on the pulse power as a function of time and they have also studied the effect of the switching rate on the spectrum of the emitted radiation. The pulses of shortest duration have the broadest spectrum. The spectral width of the R_1 ruby line of the giant pulse is broader than the line width for normal laser operation, and the beam width of the giant pulse is essentially the same as for normal lasers, i.e. about a milliradian.

In principle the energy output per pulse per unit volume of laser material should be about $1/2\ h\gamma(n_2 - n_1)$ where $h\gamma$ is the energy per photon and $n_2 - n_1$ is the population inversion density. For pink ruby and an initial inversion of, say, 50 percent one expects about one joule output per cubic centimeter of ruby. The observed output of the giant pulses are far less than the expected results. Apart from the discrepancies between theoretical and experimental energy emission, there are basic limitations in the energy per pulse that can be obtained from a single ruby laser. It turns out that it is in principle impossible to achieve a high initial inversion over arbitrarily large dimensions, which limits the size of the ruby that may be used effectively. For example, if one uses a very long ruby, a high inversion will be achieved in the central portion and not in the ends. Hence, only the middle of the ruby will participate in the laser action. The depumping of the ends is caused by spontaneous emission from the ends undergoing a large gain as it passes the length of the ruby. When the ruby is long enough the inversion at the ends is depleted in a manner independent of the reflection from the end faces of the ruby (or cavity).

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1.1.2 Threshold

The threshold for laser operation is defined by the minimum gain necessary to overcome the loss mechanisms existing in a given cavity. The gain in turn, is directly related to the energy or power which is extracted from the source. Hence, the threshold is measured in joules or watts, according to the mode of operation.

Since devices vary widely in size and configuration it is difficult to make meaningful comparisons between reported threshold values. Doping, pump source, coupling, reflectivity, crystal size, operating temperature and other factors all have a considerable effect on the threshold. Generally, it increases with doping, crystal size, and operating temperature, it decreases with increased reflectivity.

1.1.3 Efficiency

There are a number of different efficiencies which can be defined for lasers, but generally the one cited is the net conversion efficiency (source input power to laser output). However, there are two factors which set a limit on the efficiency and energetic efficiency and are characteristic of the laser medium.

Quantum efficiency is the probability that an atom in one of the pump band states will make the transition to the terminal state via the laser transition. In general there is a finite possibility that the atom will make the transition by re-radiating the pumping radiation for example. The other limiting mechanism is the energetic efficiency which is defined as the ratio of the laser transition photon energy to the pumping transition photon energy (for optical pumping).

Generally, the quantum efficiency is $\geqq 70$ percent while the energetic efficiency may be as low as 10 percent. The product of these two sets a theoretical limit on the net conversion efficiency of any device which may be constructed.

1.1.4 Doping

The doping or concentration (number/cm^3 or percent by weight) determines the maximum energy which can be stored in a unit volume since each atom can store an amount of energy $h\gamma$. The energy storage capacity can be increased by increasing the doping, but at the same time, the energy required to obtain equal populations will also increase, resulting in higher thresholds. Also, the power required for CW operation will increase since the power loss per unit volume due to spontaneous decay is directly proportional to the number of atoms in the excited state. For these reasons, it has been found advantageous to use dopings of less than one percent.

1. 1. 5 Operating Temperature

If the terminal level of the laser transition lies above the ground state, as it does in a four-level laser, then the terminal level may be depopulated by cooling the crystal. This arises from the fact that the population of the level T is proportional to the factor e^{-E_T/KT_s} where E_T is the energy of the level above ground state and T_s is the crystal temperature. The net effect is a lowering of the threshold since a smaller number of excited atoms is now required for population inversion. A similar effect is observed for three-level systems.

Semiconductor lasers are very sensitive to temperature since the band structure, which is intimately connected with the laser action, changes rapidly when the crystal is heated. Both frequency and threshold exhibit thermal effects.

1. 2 SUMMARY OF OPERATING LASERS

1. 2. 1 CW Lasers

Laser action on a continuous or quasi-continuous basis has been demonstrated in various types of active media: solid state dielectrics and semiconductors as well as gases. Some of the media available at the present time are listed in Table I, along with other properties basic to the laser action itself without regard to particular devices. It is seen that a wide variety of frequencies, conversion efficiencies, and pumping characteristics is available.

Characteristics of particular devices which have been successfully operated are given in Table II.

1. 2. 2 Semiconductor Lasers

The recent achievement of laser action in GaAs has given rise to a new field of investigation in the realm of laser technology. Its significance stems from the fact that direct conversion of electrical energy to coherent radiation takes place in a highly efficient manner. What is more important, it solves the problem of how to modulate a laser beam since the electrical pumping current can easily carry the modulating signal as well.

Current passing through a GaAs diode in the forward direction gives rise to the emission of recombination radiation in the vicinity of the p-n junction. As the current density is increased, the width of the emitted spectral line is reduced indicating the presence of stimulated emission. By controlling crystal impurities and creating an optical cavity in the plane of the junction, laser action can occur. It is believed that at high current densities operation takes place with nearly unity quantum efficiency, i. e., for every electron crossing the junction one photon is emitted. The net conversion efficiency of the device (input electrical energy to radiated energy) has been observed to be as great as 50 percent compared to the

Medium	Pumping Mechanism	Emission Frequency	Efficiency Energetic	Efficiency Quantum
$CaF_2:u^{3+}$	$0.88\,\mu$ - $0.92\,\mu$	$2.613\,\mu$	35%	--
$CaF_2:D_y^{2+}$	0.23μ - $0.49\,\mu$ (strongest) $0.58\,\mu$ $0.72\,\mu$ $0.91\,\mu$	$2.36\,\mu$	10% 20% 30% 38%	--
$CaWO_4:Nd^{3+}$	$0.59\,\mu$	$1.065\,\mu$	55%	--
$Al_20_3:C_R^{3+}$	$0.38\,\mu$ - $0.43\,\mu$ $0.5\,\mu$ - $0.6\,\mu$	$0.694\,\mu$	57% 80%	~70%
G As:(Zn, Te)	Electron Injection	$0.84\,\mu$	--	~100%
He-Ne	Gas Discharge	$1.15\,\mu$ $0.63\,\mu$	--	--

TABLE I

Medium	Threshold	Power Input	Power Output	Frequency	Temperature
$CaF_2{:}u^{3+}$	2000 watts	2 kw	10 uw	2.613 μ	77°K
CaF_2Dy^{2+}	100 watts	1 kw	350 mw	2.36 μ	27°K
$CaWO_4{:}Nd^{3+}$	1200 watts	1.6 kw	1 mw	1.065 μ	77°K
$Al_2O_3{:}CR^{3+}$	850 watts	930 w	4 mw	0.694 μ	77°K
GaAs	50 milliwatts	50 milliwatts	25 milliwatts	0.84 μ	4.2°K
He-Ne	50 watts	50 w	15 mw	1.15 μ	--

TABLE II.

present 0.1 percent for conventional lasers. Clearly, these highly efficient devices merit further investigation.

Although experimental results are sparse, some idea of the operating characteristics of present semiconductor lasers can be obtained from the partial summary given in Table III on the following page.

The band structure of the semiconductor, which is intimately related to laser action, is very sensitive to temperature. Hence, the current densities required for high power laser operation ($\sim$20,000 amps/CM^2) give rise to serious cooling problems. Operation is greatly enhanced by immersing the crystal in a low temperature bath, either liquid nitrogen (77°K) or liquid helium (4.2°K). High output powers are also obtained by pulsing the input to the junction. This procedure has yielded peak powers of 280 watts as compared to 25 milliwatts for continuous operation.

The spectral characteristics of semiconductor lasers are quite similar to those of other lasers. For GaAs the emission line is typically in the neighborhood of 8400 Å with a half width which decreases from 125 Å above threshold to approximately 2 Å below threshold at liquid helim temperatures. At high current densities heating of the p-n junction due to its series resistance causes a shift of the emission line during the pulse. This shift represents an over-estimation of the half width of the line and the reported values represent only upper limits. Of the light power output from the junction of the diode, better than 50 percent is coherent at the operating frequency. Observed beamwidths vary from 0.1° to 10°.

It has been demonstrated that by changing the chemical composition of the semiconductor crystal, e.g. doping element and/or concentration, it is possible to change the wave length of a p-n junction laser. It is estimated that such a procedure could yield frequencies anywhere in the range from 6000 Å to 9000 Å in the near future. Assuming that semiconductor laser technology progresses as rapidly as that of conventional lasers, Table IV presents likely developments for these devices within the next few years.

TABLE IV

Operating Temp.	Power Output	Beam and Spectral Characteristics
4°K to 300°K	1 - 10 kw (peak, pulsed)	10^{-4} to 10^{-6} radians beamwidth
	1 - 10 w (continuous)	6000-9000 Å operating frequency
		Less than 1 Å line width

	Material	Mode	Temp.	Threshold	Power	Beam & Spectral Characteristics
(IBM) 1.	GaAs	Pulsed		10, 000 A/CM^2	-	2 lines observed 6 Å apart and 2 Å wide 4° beam divergence
(IBM) 2.	GaAs	Contin.	4.2°K	100 A/CM^2	10-25 mw out for 50 mw in	8400 Å
(Philco) 3.	GaAs	Contin.	300°K	--	1 mw out for 120 mw in	~9000 Å
	GaAs	Contin.	77°K	--	25 mw out for 120 mw in	~9000 Å
(GE) 4.	GaAs	Pulsed	77°K	8, 500 A/CM^2	--	Coherence over 100 µ 0.1° beam divergence
	GaAs	Pulsed	4.2°K	--	--	Line narrows from 125 Å to less than 15 Å
	$GaAs_{1-x}P_x$	Pulsed	77°K	Less than 11, 000 A/CM^2	1-5 u sec input pulses 1.3 V at 20-100 ma	Line narrows: 125 Å → 12 Å 7100 Å
(MIT) 5.	GaAs	Pulsed	77°K	10, 000 A/CM^2	-- 5 u sec pulses at 13 cps input	Less 10° beam divergence Line narrows: 175 Å → 30 Å 100 Å → 5 Å
	GaAs	Pulsed	4.2°K	700 A/CM^2	280 w peak out	Multiple modes observed

TABLE 3. Characteristics of Semiconductor Lasers

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1.2.3 Solar Pumped Lasers

When sufficiently broad pumping bands are available it is possible to use the sun directly as a pumping source for a laser. This has been demonstrated using CaF_2: Dy^{2+} at liquid neon temperature. A 10" diameter condensing mirror collecting about 50 watts of power was focused on the crystal and produced a CW laser output at 2.3 μ. Relaxation oscillations were clearly present. For CaF_2:Dy^{2+} approximately 10 percent of the solar power is useful in pumping. Larger mirrors and more efficient methods of coupling the collected energy to the crystal (end pumping, for example) are expected to produce larger outputs competitive with conventional CW lasers.

Another possibility, though not quite so direct as the previous, is to pump a semiconductor laser directly from a solar cell. The low voltages (1.0-2.0 volts) used for current GaAs lasers suggests such operation. The conversion efficiency of the solar cell-semiconductor combination could approach 25 percent.

Size limitations on collector surfaces would determine the maximum power output to be expected of the above mentioned systems. Cooling problems also seem to be a non-trivial factor in CW operation of solid state lasers and would certainly be present in the case of direct solar pumping.

2.0 OPTICAL DETECTOR TECHNOLOGY

During this phase of the IRSGHL portion of the study of optical communications from deep space, much attention was devoted to possible problems in detection of highly degenerate (quantum-mechanically speaking) laser radiation. Unfortunately this work is not in a condition to report, except for the general conclusion that excess fluctuation is probably always avoidable by proper system design, and indeed may never be significant. It is recommended that system design proceed on the assumption that such excess fluctuation does not exist. A survey of the potentialities of optical and infrared detectors is presented below; the ultraviolet region below 0.2 μ is not considered because it seems to offer no advantage, and the difficulties of the technology, particularly that of present-day lasers, suggests that it is not worth further consideration. Firm data are presented for multiplier phototubes from 0.2 to 1.1 μ; estimates are given for infrared detectors to 36 μ. For further information several articles on infrared detectors in the Proceedings of the IRE for September 1959 may be consulted.

By far the best means for detection of light is the photoemissive process. An electron released from a surface may be increased to a sizeable current by a secondary-emission electron multiplier, or it may be accelerated to high velocity and detected by other means. The most useful device of this type is the multiplier phototube.

The characteristics of typical photoemissive surfaces[1] are shown in Figure 1. The envelope of these data is replotted in terms of quantum efficiency in Figure 2. The quantum efficiency is the average number of electrons emitted per incident photon; for visible or infrared light at most one electron can be released for any one incident photon. Hence this quantum efficiency factor is equivalent to an attenuation factor applied to the light beam. Except for a fluctuation of perhaps 0.30 in the relative amplitude of response of the multiplier to each photoelectron and the small dark-current noise component, both of which are often negligible, the information efficiency of a beam of light is merely degraded by this quantum efficiency factor in the detection process. Photons not detected are transmitted in vain.

The frequency response of multiplier phototubes is uniform for frequencies up to approximately 10^8 cps, and pulse rise time is approximately 3×10^{-9} sec, with a time jitter of 10^{-9} sec. There is therefore an adequate bandwidth capability for transmission of a television picture in a variety of modes of transmission of codings.

[1] Copied from "RCA Photo and Image Tubes", booklet 1CE-269 of the Radio Corporation of America, Electron Tube Division, Harrison, N.J.

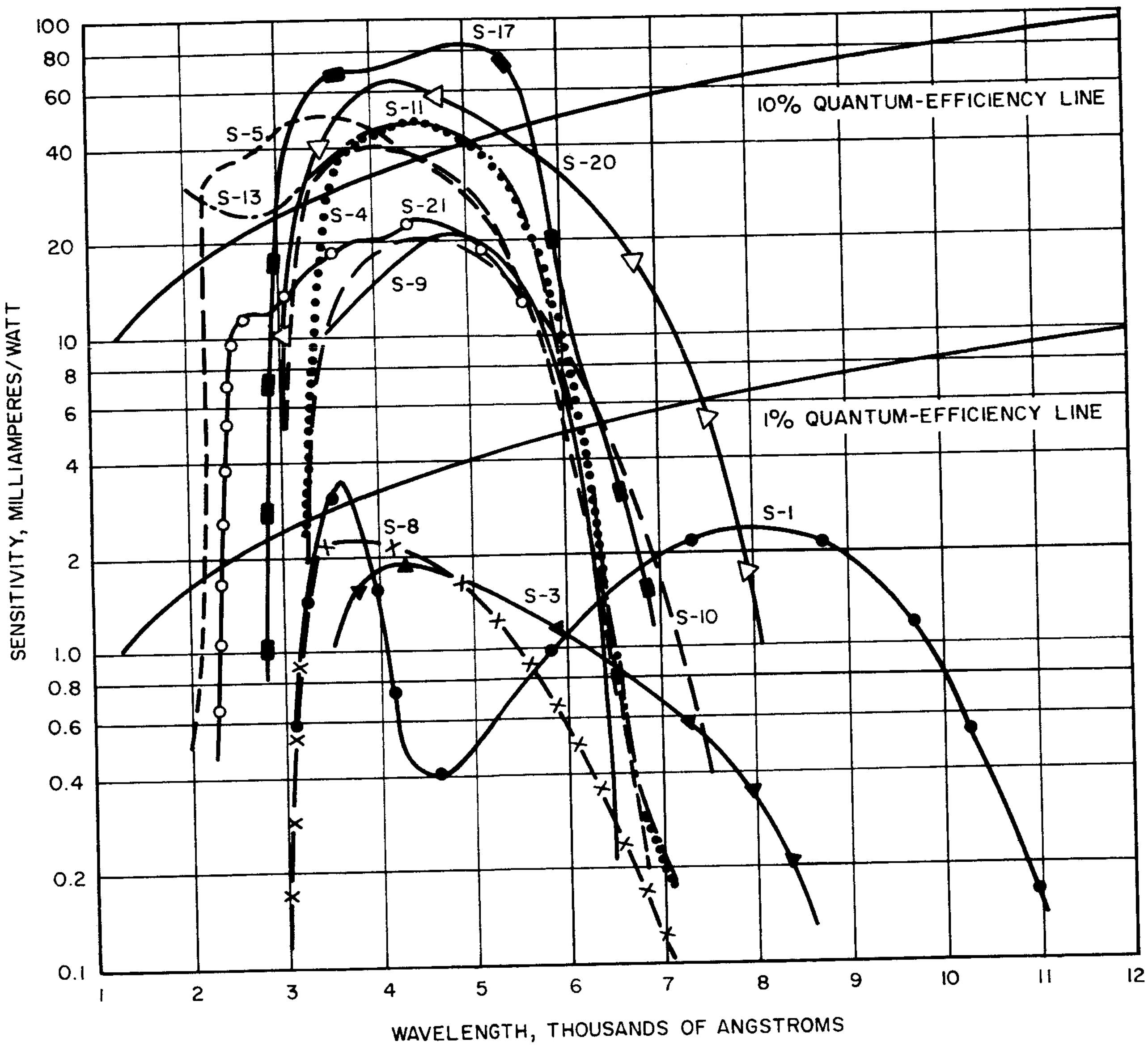

Figure 1. Sensitivity of Multiplier Phototubes

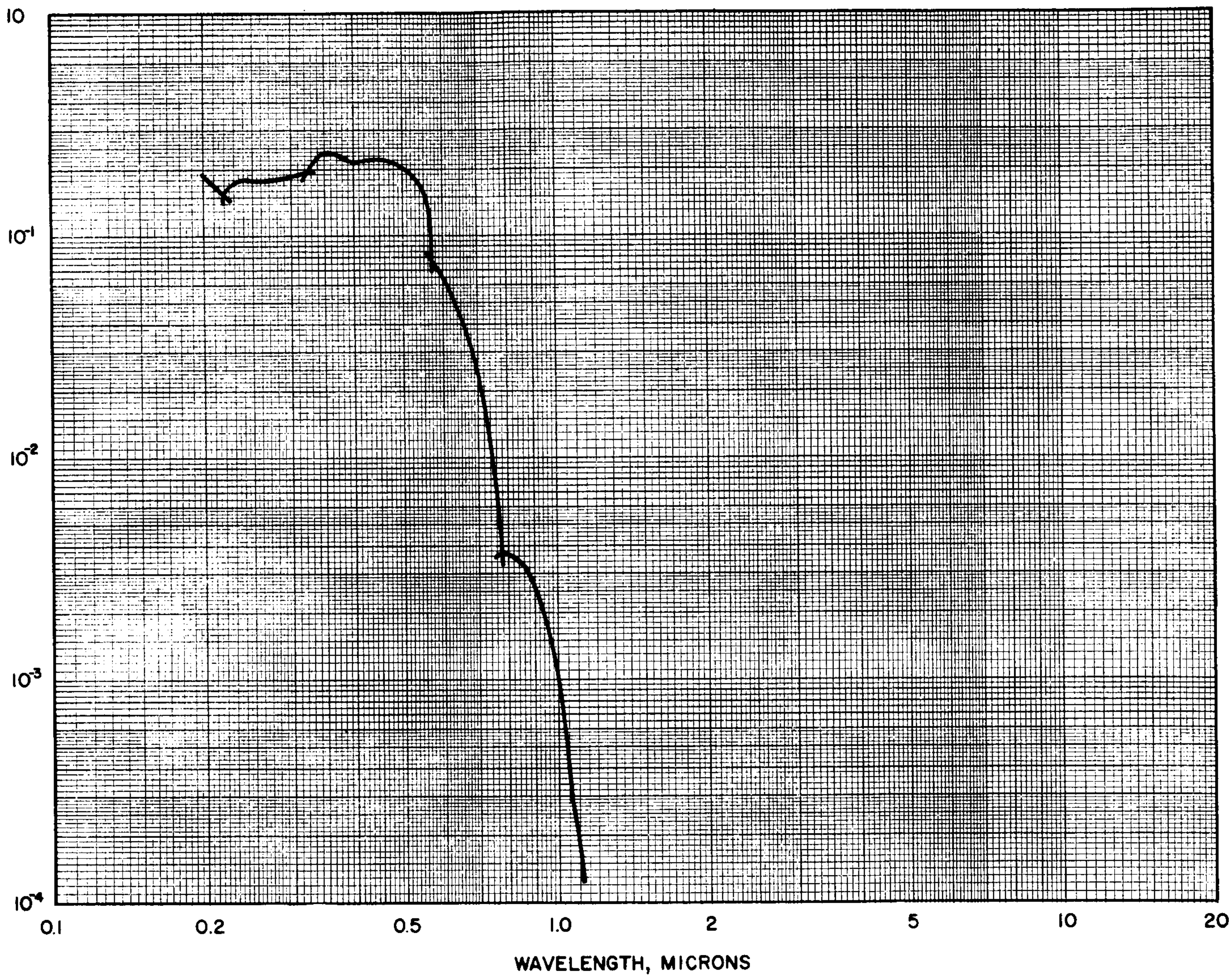

Figure 2. Quantum Efficiency of Multiplier Phototubes

Systems employing multiplier phototubes in low-background, large bandwidth operation are essentially signal-noise limited, i.e., the main noise is the fluctuation in signal photoelectrons due to random processes in transmission and detection. Such processes create a Poisson distribution in signal photoelectrons per pulse period if the number of photons transmitted is accurately known. Modulation of a quantum-mechanically degenerate laser beam may produce large fluctuations in the number of photons transmitted, and hence produce excess fluctuations in the photoelectrons in the detector, but such laser beams are not anticipated and in any event may be avoided by use of other lasers.

The theory of Jones[2] is therefore applicable, and the upper bounds to information efficiency (bits/photo; here bits/photoelectron) which he establishes can be approached as closely as skill in coding permits. In order to realize efficiency improvements from use of widely spaced pulses in a PCM system, the transmitter efficiency must remain unchanged as the duty cycle is reduced. A continuously pumped laser operating in the pulsed-reflector (gaint pulse) mode approximately meets this requirement. Pulse energy may be controlled by a feedback control technique, such that as soon as enough light has been transmitted the optical cavity regeneration is reduced. There is thus at least a theoretical capability of generating the type of beam to which Jones' analysis applies.

Other types of photoemissive detectors, such as image orthicons and image intensifiers, microwave phototubes, and various optical-mixing superheterodyne techniques provide capability for unique types of signal processing, involving imaging, extremely wide band amplification, or very narrow optical bandwidth. However, no need exists in the present system for any of these capabilities. The only deficiency of multiplier phototubes worthy of discussion here is their spectral response: The maximum quantum efficiency at 1.1 u is only 0.01 of that at 0.55 u, and this steep decline continues further into the infrared.

The military utility of infrared systems has engendered development of a host of new infrared detectors since 1940. The better of these have time constants less than 10^{-7} sec. and provide substantial power amplification prior to the input of their preamplifiers.

The quantum efficiency of these detectors is quite high, but noise other than signal noise is dominant. The PbS and PbSe thin-film detectors and the InSb and doped germanium crystal detectors will, when appropriately cooled, be limited by fluctuations produced from detection of the radiation flux incident upon them from room-temperature surroundings. If this radiation is reduced, tenfold[3] improvement in signal-to-noise ratio may be realized. However, the detector time-constant generally increases

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[2] R. C. Jones, "Information Capacity of a Beam of Light", J. Opt. Soc. Am. 52, 493-501 (May 1962). See also Section No. 4 of the interim progress report on Contract No. NAS 9-879, 7 November 1962 through 7 January

in such circumstances due to the reduction in the number of carriers in the semi-conducting detector material. Moreover, it is not known if more than tenfold improvement may be obtained, and indeed if such improvement may be obtained at all for very tiny detectors because of their smaller initial noise power.

Because of the very narrow optical bandwidth required for this system, it is expected that ambient radiation can be made negligibly small. Therefore, the exact level of performance to be expected remains uncertain. Detector performance is generally stated[4] in terms of power detectivity, D*, either for thermal radiation of a specified temperature, usually 500°K, or spectrally pure radiation; the peak value of the D*(λ) curve is often cited.

$$D^* = \frac{A^{1/2}(\Delta f)^{1/2}}{NEP}$$

where

A = area of detector, cm^2

Δf = electrical noise bandwidth, cps

NEP = noise-equivalent radiation power

If we assume a detector area of 0.001 cm^2 and limit of a tenfold improvement in D*, we obtain

$$NEP \cong \frac{3 \times 10^{-3}(\Delta f)^{1/2}}{D^*}$$

Furthermore one may naively assume that no change occurs in the detector time constant, and hence establish a minimum detectable energy for a detector by considering use of pulses appropriate to the published detector time constants. A noise-equivalent number of photons may then be computed:

$$NEQ \cong \frac{3 \times 10^{-3} \tau^{1/2} \lambda}{D^* \sqrt{2}\, hc} \cong \frac{\tau^{1/2} \lambda}{D^*} \times 10^{13}$$

where D* is given in cm $cps^{1/2} w^{-1}$, τ in μsec, and λ in μ.

A few values of this parameter for some of the best detectors are presented in Table I. The data were taken from a recent survey article[5]. The response is approximately the same for wavelengths shorter than those given. Therefore the results may be summarized as follows: Infrared

[3] W. Haynie, C. Gramm, and A. Prasil, "Semi-Annual Report on a Space Background Study", Contract DA-30-069-ORD-2803, Eastman Kodak Co., Apparatus and Optical Division, Rochester, N.Y. (Jan. 16, 1961).

[4] R. C. Jones, "Performance of Detectors for Visible and Infrared Radiation", Advances in Electronics, Academic Press Inc., New York (1953).

[5] W. L. Wolfe and T. Limperis, "Quantum Point Detectors", Space/Aeronautics Magazine, November 1961.

detectors operated in an ideal manner may be characterized by a noise-equivalent number of photons received in each period of time equal in duration to the detector time constant. For wavelengths up to 5μ this NEQ is 10^3, and for wavelengths up to 36μ it is 10^4.

It should be noted that this noise is much more important than signal noise because it may cause a false indication when no pulse has been sent. It is equivalent to ambient radiation values of $A = 10^6$ and 10^8 in Jones' analysis[2]. Moreover, system operation will be even less efficient if pulse width is not matched to detector time constant; this could be an awkward restriction except for the fact that none of the time constants are unduly short.

It must be emphasized that the NEQ analysis presented here is quite arbitrary, but hopefully suited to the system requirements. The choice of detector size and permissible improvement factor was imply a matter of estimation; a smaller detector could be utilized but then less improvement (perhaps none) from reduction of radiation could be anticipated.

Table I. NEQ of IR Detectors

Sensitive Material	Wavelength (microns)	Time Constant (μ sec)	Peak Detectivity (cm $cps^{1/2} w^{-1}$)	NEQ Photons
InSb	5.0	<1	6×10^{10}	8×10^2
Ge:ZhI	36	<0.1	1×10^{10}	1.1×10^4
PbS	2.0	150	10^{11}	2.4×10^3
PbSe	4.5	18	4.4×10^{10}	4.3×10^3
P-type Ge:Au	5	<0.1	1.5×10^{10}	1×10^3

A somewhat similar treatment[6] has been given by Jones; the foregoing may serve to make his comprehensive analysis more meaningful for our application. A good general discussion[7] of infrared detectors by Gelinas and Genoud presents the theory of signal-noise and background-noise limitations in a clear, consistent manner, although the particular data of interest still are not available.

[6] R. C., "Information Capacity of Radiation Detectors II", J. Opt. Soc. Am. 52, 1193-1200 (Nov. 1962).

[7] R.W. Gelinas and R.H. Genoud, "A Broad Look at the Performance of Infrared Detectors", RAND Corporation, P-1697, (May 11, 1959).

One detector which has received much publicity is the silicon photodiode or phototransister. These detectors suffer from junction capacitance and Johnson-Nyquist noise in such a manner that high frequency response is only obtainable at the expense of weak-signal detectability. Recent measurements[8] and calculations indicate a low-signal NEQ of 5×10^4 for a time constant of 100 μ sec, and hence they are much inferior to S1 photosurfaces.

It should be remembered that it is theoretically possible to obtain performance as predicted by the high quantum efficiency ($\sim$0.5) of infrared detectors only if noise sources can be eliminated. Some type of low-temperature amplifier is probably needed, and elimination of noise sources in the detectors themselves is surely not complete even without ambient radiation. The foregoing estimation therefore provides a means for making an interim appraisal of the effectiveness of infrared wavelengths for communication; if an infrared system seems to be at all attractive, a detector study program should be undertaken to evaluate the best detectors in the mode of operation appropriate to the system being considered.

[8] R. K. Schisler, unpublished data (Hughes Aircraft Company)

APPENDIX A

LASER BIBLIOGRAPHY

In an area of technology which is as rapidly moving as the Laser field, no bibliography can claim to be complete. In fact, it is likely to become obsolete during its preparation.

The interest which has been stimulated in these devices has resulted in an enormous number of lay as well as truly professional articles ranging from pure theoretical speculation to systems applications. To attempt to be inclusive would have been sheer folly. Since most of the lay articles add no new material to the body of scientific knowledge, but have the purpose of instructing the uninitiated rather than informing the expert, these are not represented here. Some degree of selectivity has been natural in the process of the preparation of this list, but no attempt was made to truly formalize the rules for acceptance or rejection of a given article. Moreover, time did not permit the annotation of this list, but it is hoped that this can be done at least for the more important papers at a later date.

Recently a number of surveys have been published and as a result it is possible to suggest a rather small number of journals and a book which will serve as handy reference sources for both the expert and the laymen.

These are the following:

LASERS - Generation of Light by Stimulated Emission - Bela A. Lengyel, John Wiley and Sons, Inc., N. Y., 1962.

Written by Dr. B. A. Lengyel of the Hughes Research Laboratories at Malibu, this book is the first to offer a unified exposition of the principles of lasers and recent progress in the field. It is written at a level and with such clarity as to make it readily understandable to the interested layman as well as the professional.

APPLIED OPTICS - Supplement No. 1 - Optical Masers - 1962

Published by the Optical Society of America, this journal contains survey articles by internationally known specialists in the field.

PROC IEEE - Quantum Electronics Issue, January 1963

Published by the IEEE, this issue contains survey articles on properties and applications of the device. Together with the journal above, most of the now-classic papers on special topics in the field are represented.

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